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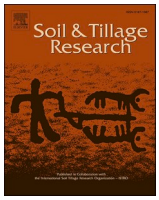

# Effect of organic material addition on active soil organic carbon and microbial diversity: A meta-analysis

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ABSTRACT

Organic materials are integral to the soil carbon cycle in agricultural ecosystems, yet their specific impacts on soil organic carbon (SOC) and microbial diversity are not fully understood. In this study, we analyzed 188 data pairs from 57 published papers to assess the effects of various organic materials on SOC composition and microbial diversity across different farmlands. Our findings indicate that the addition of organic materials consistently enhances SOC composition and promotes both bacterial and fungal diversity. Notably, the particulate organic carbon (POC) fraction exhibited the most significant increase (42.35%), suggesting that POC is the primary pathway for organic carbon accumulation. Our analysis also identified the type of organic material as the leading factor influencing soil active carbon fractions and microbial diversity, with compost emerging as the most effective material for boosting soil carbon sequestration and microbial richness. Interestingly, while both dissolved organic carbon (DOC) and microbial biomass carbon (MBC) increased with organic material addition, a negative correlation between these two components was observed. This study advances our understanding of the complex interactions between organic materials, SOC components, and microbial diversity, providing valuable insights for the development of sustainable soil management practices aimed at enhancing soil carbon storage and agroecosystem health.

## 1. Introduction

In agroecosystems, organic material addition is the main form of carbon input, while soil mineralization is the main form of carbon output (Li et al., 2018; Xie et al., 2022). SOC stability is mainly related to soil organic carbon composition and agricultural management practices (Wang et al., 2015; Xiao et al., 2019; Zhou et al., 2019; Zhu et al., 2014). Dissolved organic carbon (DOC), particulate organic carbon (POC), microbial biomass carbon (MBC) and easily oxidizable organic carbon (EOOC) represent the active SOC fraction (Lin et al., 2022; Mi et al., 2016), and are considered early, sensitive indicators of SOC changes in response to management practices (Chen et al., 2018; Guo et al., 2020). The active organic carbon fraction is the main source of energy for soil microorganisms, which not only regulates crop nutrient effectiveness and optimizes soil physicochemical properties, but also participates in SOC turnover (Zhao et al., 2021; Zheng et al., 2022). In addition, the active SOC fraction has a significant effect on soil microorganisms (Huang et al., 2021), while the content and composition of the active fraction are also influenced by microorganisms (Campbell et al., 2021; Zhang et al., 2021). Therefore, understanding how active organic carbon fractions and microbial communities respond to organic material additions is important for maintaining favourable soil carbon levels for agroecosystem species.

The application of organic fertilizers significantly influences the dynamics of SOC fractions, a concept well-established through extensive research. A decadelong experimental evidence suggests that the use of organic fertilizers enhances the formation of soil macroaggregates and boosts the levels of reactive carbon components, including dissolved organic carbon (DOC) and microbial biomass carbon (MBC) (Zhao et al., 2021). Additionally, biochar has been recognized for its role in expediting SOC sequestration by elevating the levels of more recalcitrant SOC fractions and altering the composition of the soil microbial community (Zheng et al., 2022). Prolonged investigations spanning over three decades reveal that the incorporation of organic materials, such as

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straw and manure, can elevate SOC levels without significantly affecting DOC levels (Marschner et al., 2003). In the short term, straw amendment has been noted to enhance the levels of labile soil carbon fractions, including DOC, easily oxidizable organic carbon (EOOC), and MBC (Zhu et al., 2015).

The relationship between organic material inputs and SOC fractions is well-documented, with a consistent positive correlation between carbon inputs and the enhancement of DOC and MBC (Qiu et al., 2023; Wang et al., 2015). However, there is evidence to suggest that the introduction of organic materials can, in some cases, hasten the mineralization of organic carbon due to stimulation effects, subsequently diminishing the content of active components (Li et al., 2018; Liu et al., 2022; Oladele and Adetunji, 2021; Xiao et al., 2018). Such variations can often be ascribed to differing climatic conditions, soil textures, types of organic materials, application rates, and timing of application (Fang et al., 2018; Li et al., 2020; Liu et al., 2006; Sarker et al., 2022; Tang et al., 2022).

The application of organic fertilizers is known to stimulate soil microbial activity, thereby accelerating the turnover of SOC (Marschner et al., 2003). DOC has been identified as having a more pronounced effect on fungal communities, whereas MBC and EOOC are primary determinants of bacterial community health in the soil (Zhang et al., 2021). Moreover, the exploration of soil organic carbon components and microbial communities has been extended to various processes, including vegetation restoration (Dou et al., 2023), cultivation of legume crops (Li et al., 2023), and the implementation of no-tillage practices (Li et al., 2021). The integration of organic materials into agricultural practices has been shown to enhance both crop productivity and soil microbial diversity (Cong et al., 2020; Shu et al., 2022). These studies are instrumental in shedding light on the effects of organic material amendments on the diversity of soil microorganisms. While it is acknowledged that organic materials contribute to microbial diversity, the precise interplay between these materials and soil active components (DOC, POC, EOOC, and MBC) in relation to microbial diversity remains to be fully elucidated.

Here, we conducted a global meta-analysis of soil DOC and MBC, while investigating changes in fungal and bacterial diversity. In this study, we aimed to answer the following three questions: (1) the impact

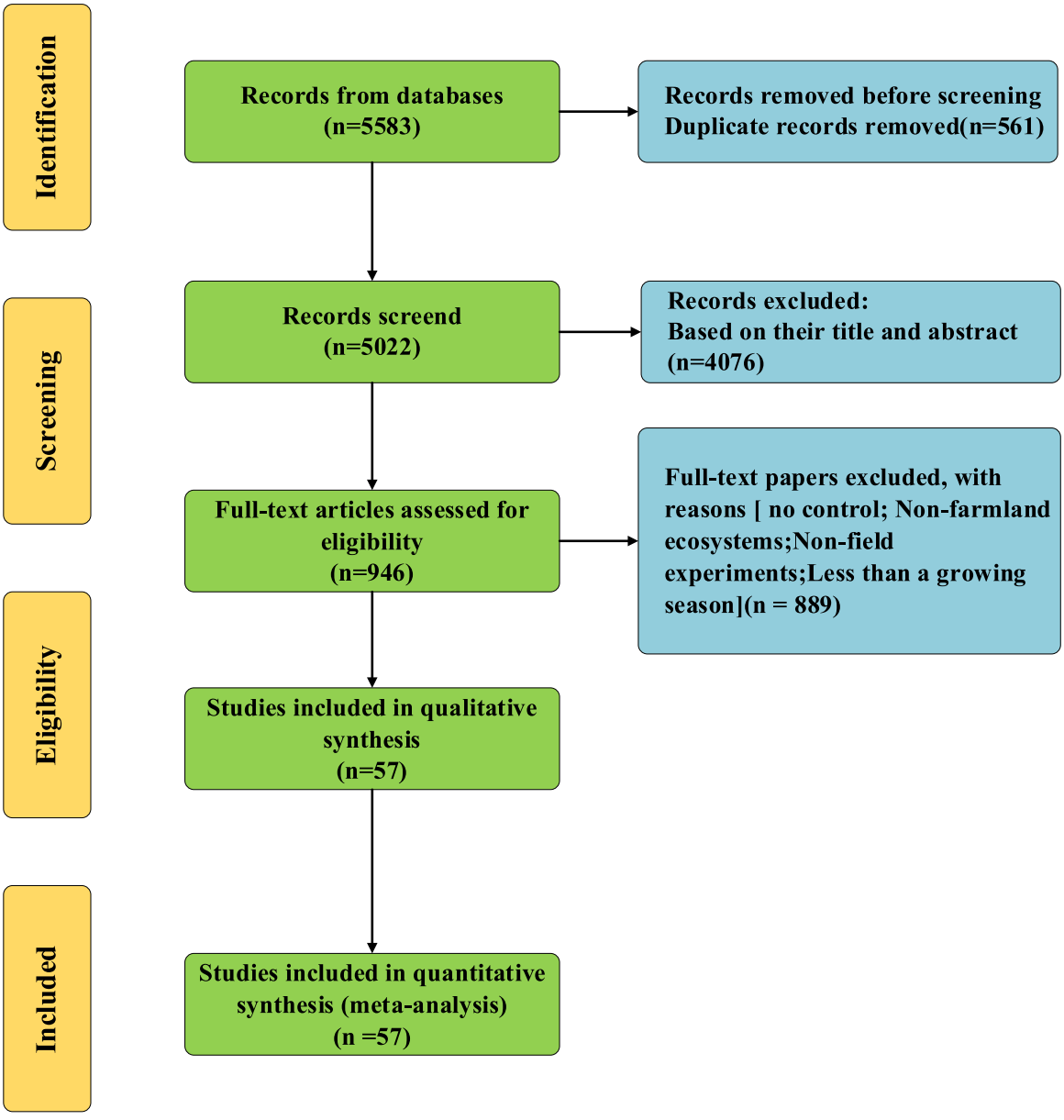
Identification
Screening
Eligibility
Included
Records from databases (n=5583)
Records removed before screening Duplicate records removed(n=561)
Records screend (n=5022)
Records excluded: Based on their title and abstract (n=4076)
Full-text articles assessed for eligibility (n=946)
Full-text papers excluded, with reasons [ no control; Non-farmland ecosystems;Non-field experiments;Less than a growing season](n = 889)
Studies included in qualitative synthesis (n=57)
Studies included in quantitative synthesis (meta-analysis) (n =57)

**Fig. 1.** PRISMA diagram showing the process of locating publications included in the present meta-analysis.

of organic materials on active SOC components in farmland, (2) the key factors that regulate the active components of soil organic carbon when organic materials are added and (3) the relationships between active carbon fractions and microbial diversity.

## 2. Methods

### 2.1. Data collection

We systematically searched all peer-reviewed journal articles and theses that investigated the effects of organic materials on microbial diversity, using the Web of Science, ScienceDirect and China National Knowledge Infrastructure, up to 30 November 2022. The literature was screened according to PRISMA (Fig. 1). Search with different combinations of keywords, namely (soil microbial communities OR soil microbial diversity OR soil microbial biomass) AND (dissolved organic matter OR dissolved organic carbon OR DOM OR DOC). The articles were reviewed to evaluate whether the studies satisfied the following specified criteria: (1) the experiment was conducted for no less than one growth season in a farmland ecosystem; (2) the amount of DOM or MBC could be obtained from text, tables, or graphs; (3) scientific control experiments were set up; and (4) the sample size, mean, standard deviation, or standard error were collected for the control and measured values in each study.

If only standard errors were reported in the literature, we converted the data to standard deviations according to the sample size in Eq. (1). If neither the standard deviation nor the standard error was reported, we estimated the missing values using the "metagear" package (Lajeunesse, 2016).

$$SD = \sqrt{n} * SE \tag{1}$$

where n is the number of samples in the control or treatments, and SD and SE are the standard deviation and standard error for the control and treatments, respectively.

If a publication reported multiple experiments that were conducted under varying abiotic conditions, such as different locations, seasons, amounts of organic matter, and soil layers, each experiment was considered an independent observation. We utilized Getdata 2.20 software (http://www.getdata-graph-digitizer.com/) to digitally extract data from graphical representations of the results. We compiled a meta-dataset consisting of 188 observations from 58 studies encompassing drylands, paddies, and paddy-dryland systems. (Fig. 1 and **Fig.S1**).

For each study, we extracted soil properties, such as pH, soil bulk density (BD), DOC, MBC, POC, EOOC, SOC, total nitrogen (TN), and dissolved organic nitrogen (DON). In this meta-analysis, the Shannon index was utilized to represent the diversity of bacteria and fungi. In addition, the farmland type, organic material parameters (including addition duration and organic material dosage), sampling depth and initial pH($pH_0$) were recorded for each study. To acquire climate data that were not found in the literature, the MAP and MAT were acquired from the World Climate Database (https:/ /www.world climate.com). Moreover, we categorized the data based on various factors including organic material type (biochar, compost, green manure, manure and straw), farmland type (dryland, paddy and paddy-dryland), initial soil pH levels (pH <6, 6 <pH <8 and pH> 8), and soil depth (0–10 cm, 0–20 cm, 20–40 cm and > 40 cm).

### 2.2. Meta data analysis

The effect size of organic materials on microbial diversity and soil properties was evaluated using the natural log-transformed response ratio [ln(RR)], as proposed by Hedges et al. (1999). The calculation of [ln(RR)] followed this formula:

$$\ln(RR) = \ln(X_t/X_c) \tag{2}$$

where [ln(*RR*)] is the effect size in an individual observation, $X_c$ represents the mean for the control group, and $X_t$ represents the mean for organic material addition.

An individual observation's sampling variance (vi) was computed using the following formula (Hedges et al., 2010):

$$v_i = \frac{S_t^2}{N_t X_t^2} + \frac{S_c^2}{N_c X_c^2} \tag{3}$$

where $N_t$ and $N_c$ are the number of samples in the treatment and control, respectively, and $S_t$ and $S_c$ are the standard deviations for the treatment and control, respectively.

We used the maximum-restricted natural method to calculate the cumulative effect value with the "metafor" package (Viechtbauer, 2010). For the convenience of interpretation, ln (RR) and its corresponding confidence intervals (CIs) were used as the effect sizes. Similar to previous studies (Chen et al., 2019; Hu et al., 2023; Shu et al., 2022; Wang et al., 2023), if the 95% CI of ln (*RR*) did not pass through zero, the effect of organic materials on this variable was considered significant. The test of moderators ($Q_M$) was used to compare the natural log of the response ratio of the target variables to the type of organic material, farmland type, soil $pH_0$ or soil depth. Subsequently, the analysis of publication bias was conducted using the "funnel" function in the R package "metafor". The modified version of Egger's test was used to evaluate asymmetry in the null model residuals of the funnel plot (Egger et al., 1997; Nakagawa and Santos, 2012; Yang et al., 2022a) (Table S1). A significant effect could be converted to a nonsignificant effect by Rosenthal's fail-safe number (Nfs) (Rosenberg, 2005). Irrespective of any potential publication bias exists, the results could be robust if Nfs exceeds 5 n + 10 (n, number of observations; Table S1).

### 2.3. Statistical analyses

To explore the extent to which the different factors affect variables, we chose a model based on the Akaike information criterion (AIC) to distinguish between important and nonessential predictors of the type of material, application time, application size, type of farmland, MAT and MAP on variables (SOC, DOC, MBC, POC or EOOC). According to the AIC values, the smaller the AIC is, the better the model fit. This analysis was conducted using the "glmulti" package (Calcagno and de Mazancourt, 2010).

To mechanistically clarify the effects of organic materials on SOC, DOC, and MBC, we established a structural equation modelling (SEM) path analysis with the "lavaan" package (Rosseel, 2012). Standardize processing was conducted before data analysis, which has the advantage of being unbiased by small sample size. We evaluated the standardized path coefficients ($R^2$) from the final model after 999 bootstraps. All the data were analysed in R 4.2.1 and OriginPro 2022b.

## 3. Results

### 3.1. Overall effects of organic material addition

Across all farmland types, organic materials significantly decreased BD, with a mean effect size of −0.05 (95% confidence intervals ranging from −0.065 to −0.035). In contrast, there was a significant enhancement in soil properties, including DOC, SOC, TN, MBC, POC and EOOC, with effect sizes varying from 0.21 to 0.42. Additionally, there was only a small effect of organic material addition on soil microbial diversity (Fig. 2**,** bacteria: 0.029, 0.010–0.048; fungi:0.032, −0.040–0.104).

### 3.2. Response of soil properties among different groups

The influence of organic materials on soil SOC, DOC, MBC, POC and EOOC depends on material type, farmland type, initial soil pH and soil depth (Fig. 3). Significant variances were observed in the effects on soil

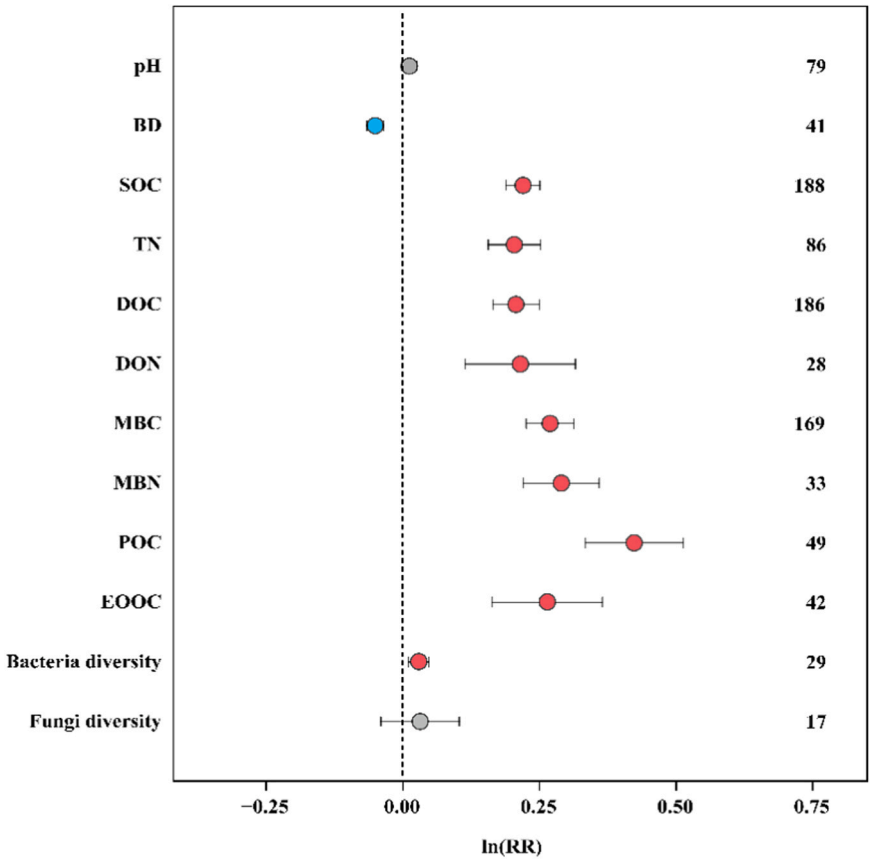


**Fig. 2.** Effects of organic materials on soil microbial diversity and soil properties.

DOC ($Q_m$ = 40.73, p <0.01) and MBC ($Q_m$ = 23.27, p <0.01), with compost, manure, and straw notably elevating DOC levels. With the exception of green manure, all other materials significantly boosted soil MBC content. However, the mean effect values of DOC and MBC in different farmland types were significantly improved. The addition of organic materials significantly increased carbon fraction in dryland soil.

Soil pH and soil depth affect soil carbon storage and microbial diversity through different pathways and mechanisms, and understanding how these factors affect soil ecosystems can help us better manage and conserve soil resources. For $pH_0$, there was no significant effect in the DOC, MBC and POC, but ln (RR) of SOC (0.33) was higher at soil pH>8. SOC decreased with increasing soil depth, but there was no significant difference in DOC, MBC and POC with soil depth. Notably, the accuracy of the results is limited by the sample size of the subgroup analysis.

### *3.3. Links between soil properties and microbial diversity with organic material addition*

We performed a correlation analysis of climatic factors, soil characteristics, and microbial diversity (Fig. 4**)**. The amount of organic matter applied only had a significant positive effect on POC, but the application time significantly affected soil pH, bacterial diversity, MBC, and DOC. Moreover, there was a significant positive correlation between bacterial diversity and both MAP and POC. SOC significantly decreased soil pH, but showed a significant positive correlation with the POC content. DOC content was significantly positively associated with MBC and POC, and climate factors also had a significant effect on MBC.

We performed model fitting for SOC, DOC, MBC, POC and EOOC, and determined the model fit according to the AIC values (**Fig.S2**). As the AIC decreases, the model's fit improves. Six factors are important for SOC as shown in Fig. 5. Material type was the only important variable for MBC, and the applied amount was the most important variable for POC. Although no significant factors affecting microbial diversity were detected, bacterial diversity was more strongly affected by climatic factors and the time of application had a greater effect on fungi (Fig. S3).

To explain how environmental factors and fertilization affect DOC and MBC contents, we constructed an SEM (Fig. 6**)**. The relative fit index for the final SEM was 95.5%. Fertilization had a positive effect on DOC but also negatively affected pH (-0.80, p <0.001). pH had a positive effect on MBC (0.87, p <0.001), and MBC was negatively correlated with DOC (-0.69, p < 0.01) and POC.

## 4. Discussion

### *4.1. Positive effects of organic material addition on SOC*

Organic material addition significantly enhanced the SOC and TN contents of agroecosystems. Several studies have indicated a positive correlation between the input of organic materials and the content of SOC (Lin et al., 2022; Qiu et al., 2023; Wu et al., 2021). Due to differences in source and preparation processes, the characteristics of the organic materials differed significantly, which in turn led to a significant difference in their effect on soil organic carbon (p<0.01). Compost, in particular, has been noted for its ability to increase SOC more effectively due to its higher content of aromatic compounds, which are beneficial for carbon fixation (Wang et al., 2022; Yang et al., 2022b). Furthermore, since the addition of organic materials can change or reshape microbial community structure by stimulating microbial secretions and community quenching, an increase in soil organic matter may be accompanied by a stimulating effect, which in turn promotes the mineralization of soil organic carbon (Rasul et al., 2022). Microbial diversity was strongly and positively correlated with organic carbon content in our meta-analysis, in agreement with the findings of a most previous studies (Wang et al., 2021). No statistically significant differences in SOC changes were

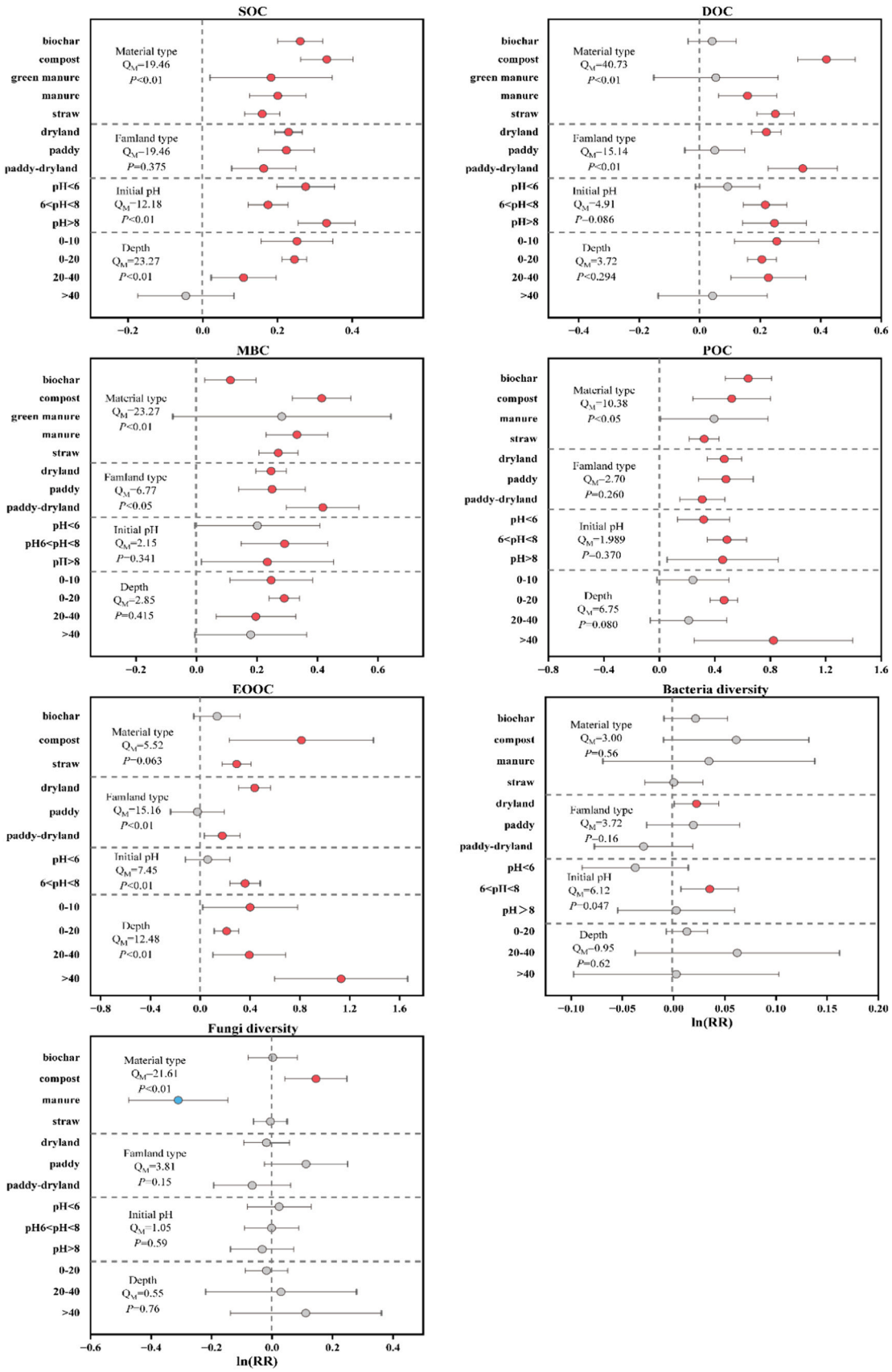


**Fig. 3.** Effects of organic materials addition on the responses of soil C and microbial diversity. The dashed line was drawn at mean ln(RR) = 0. Error bars represent 95% confidence intervals (CIs), and the numbers to the right of the CI are the numbers of observations and studies (in parentheses). If 95% CI does not overlap zero, the effect of organic materials addition on a variable is considered significant at different levels.

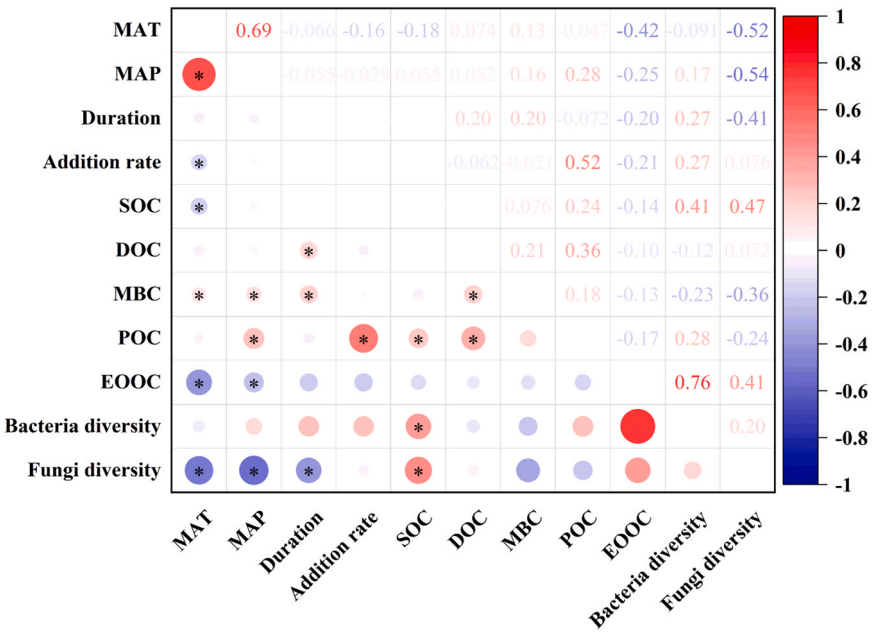


**Fig. 4.** Pearson correlation analysis between soil C contents, microbial diversity and plant biomass. The color of each circle is proportional to the value of Pearson's correlation coefficient. Red indicates a positive correlation; Blue indicates a negative correlation (* $p < 0.05$).

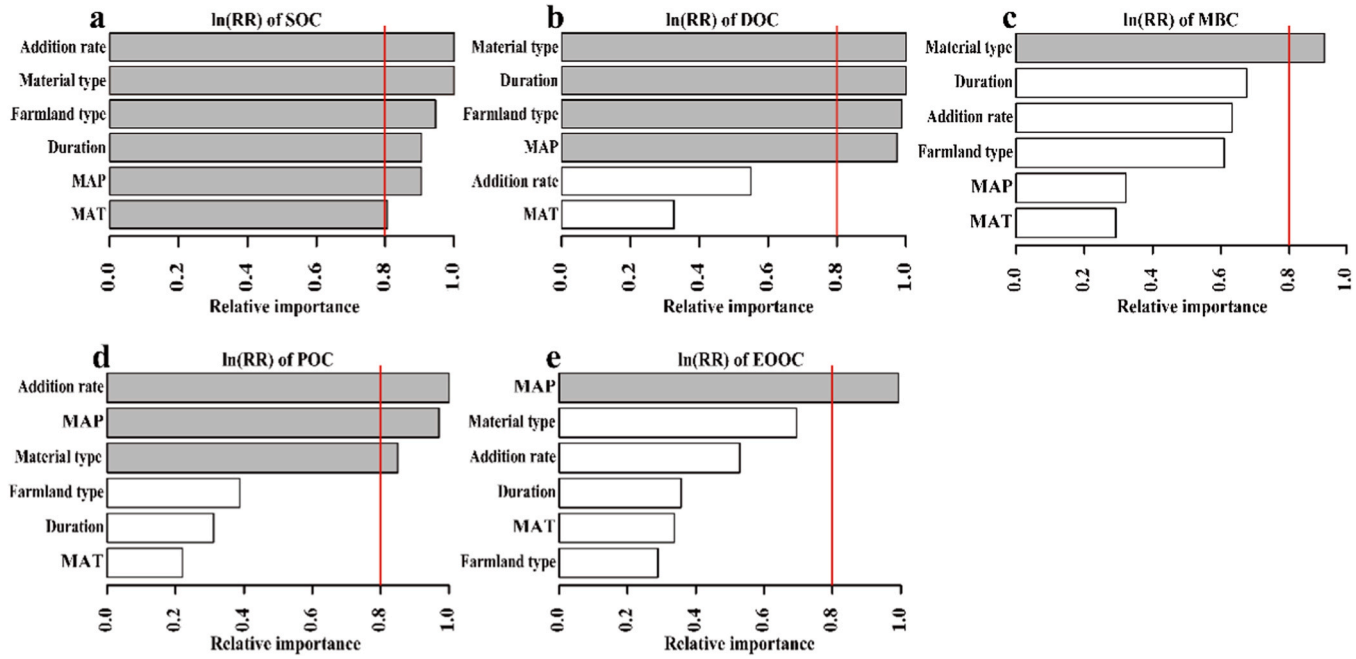


**Fig. 5.** Relative importance of factors of the effects of organic materials addition on soil C based on the sum of Akaike weights derived from the model selection using corrected Akaike's information criteria. A cut-off of 0.8 was set to differentiate between important and non-essential predictors.

detected among the different farmland types, but anaerobic conditions inhibited soil organic matter transformation and nutrient cycling (Wei et al., 2022). The alternation of aerobic and hypoxic conditions in soils with water-drought rotation was conducive to carbon stability, possibly due to the continuous screening of microbial communities due to the changing soil environment.

### 4.2. *Effect of organic material addition on active organic carbon*

The active fraction of SOC plays a crucial role in the soil carbon cycle as it is the stable fraction of soil organic matter and provides energy for microbial biochemical processes. Material type was the primary determinant of the active fraction of SOC. Compost had greater effect on DOC, MBC, and EOOC due to its high content of organic matter and ease of nutrient release during fermentation. However, biochar and green manure had no significant effect on DOC, and DOC was not significantly correlated with SOC (Yang et al., 2018). Such phenomena have been previously reported in studies, showing that biochar application increases recalcitrant aromatic and phenolic functional groups in soil compounds and increases them compounds more than SOC, sometimes also decreasing the DOC content and consequently the abundance of bacteria and fungi (Zheng et al., 2022).

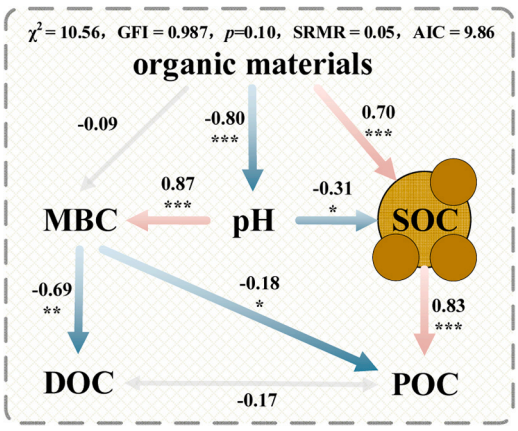


**Fig. 6.** Structural equation modeling (SEM) depicting the multiple relations of soil active carbon with environmental factors at the global scale, and the values are the standardized path coefficients from model. The red lines are the positive relationships and the blue lines are the negative relationships, respectively. Arrows represent a directional influence of one variable upon another. The numbers beside the arrows are standardized path coefficients. $R^2$ stands for the amount of variation interpreted by variables, which 0is calculated after 999 bootstraps, and the significant level is set at *p < 0.05, **p < 0.01, ***p < 0.01.

Overall, POC was most affected by the organic material, with an average increase of 42.35%. SOC showed a significant positive correlation with POC, but not with MBC, DOC or EOOC, indicating that the increase in SOC in soil was mainly due to POC and that POC was a more responsive indicator of SOC changes (Chen et al., 2018). Organic materials can promote root development and root secretions, enhancing the agglomeration of organic matter with soil to increase soil POC levels and improve POC stability and accumulation (Witzgall et al., 2021; Yang et al., 2018). The most significant increase in POC occurred with biochar addition, which further indicates that the interaction of functional groups in organic materials with minerals or the adsorption of soil organic matter to organic materials can result in the formation of soil particle agglomerates. POC accumulation and stability are enhanced by increased organic material application, which can increase soil POC content (Qiu et al., 2023).

Greater carbon inputs (rice roots, root secretions and straw) were applied to paddy crops than to dryland soil crops, which led to greater carbon availability and could result in greater microbial biomass and DOC and MBC contents (Wei et al., 2022). However, our analysis revealed that the addition of organic material changed this phenomenon. Organic materials not only change the microbial community structure, but also had significant amounts of DOC and MBC, which may mask this difference.

MBC and DOC have relatively large effects on microbial communities (Yan et al., 2020) and remain well coupled. Interestingly, we found that both DOC and MBC increased due to organic material addition, and there was a significant positive correlation, but SEM analysis revealed a negative effect of MBC on DOC, revealing a significant competitive relationship between DOC and MBC. To avoid interference from organic materials, we used control data analysis to reveal an inverse correlation between MBC and DOC, further demonstrating the existence of this competitive relationship (**Fig.S1**).

Soil microorganisms decompose DOC to acquire energy and nutrients, which in turn increases their biomass, or MBC (Taylor and Bhatnagar, 2024). As DOC is assimilated by these microorganisms, it is converted into microbial biomass, suggesting that a higher DOC content can foster a more vibrant microbial community. Microorganisms also produce new DOC during their metabolic processes, originating from excretions, extracellular polysaccharides, and lysed cellular material (Bandopadhyay and Shade, 2024; Taylor and Bhatnagar, 2024). This indicates that MBC contributes to the generation and sustenance of DOC (Song et al., 2022). However, this reciprocal transformation involves competition; microorganisms must obtain adequate energy and nutrients from DOC for their growth, potentially depleting DOC levels (Xiong et al., 2023). Additionally, the death and decomposition of microorganisms release carbon and nutrients back into the DOC, which could decrease MBC.

### 4.3. *Effect of organic material addition on microbial diversity*

Carbon utilization efficiency is influenced by microorganism diversity (Domeignoz-Horta et al., 2020). In our analysis, differences were evident in the response rate and factors influencing bacterial and fungal diversity upon organic material application. A no fertilizer treatment or organic material treatment significantly increased the bacterial microbial diversity compared to that under pure mineral fertilization, while fungal diversity was less responsive to organic material addition. These results are consistent with previous meta-analyses (Shu et al., 2022). When the organic material was further divided by type, there were significant differences in their effects on fungal diversity. A greater increase in soil bacterial and fungal diversity was observed in response to compost, possibly because compost is rich in readily decomposable organic matter and contains an abundance of microorganisms (Fig. 2).

In addition to the influence of exogenous substances, microbial diversity shows obvious spatial characteristics. Low soil microbial diversity was found at high latitudes, and high diversity was found at low latitude sample sites (Liu et al., 2014, 2015). Xiao et al. (2021) reached the same conclusion in their study of the latitudinal distribution pattern of soil microbial β-diversity. The latitudinal distribution pattern of microbial diversity was influenced by both temperature and soil heterogeneity, but temperature may be more important than soil heterogeneity in mediating microbial diversity.

Soil microorganisms are the primary consumers of energy and oxygen, and pH is one of the important factors affecting the diversity of soil microbial communities (Zhalnina et al., 2015). The bacterial communities present in acidic soils exhibit lower abundance and diversity than those in neutral and alkaline soils (Zhang et al., 2022b), which may be mainly due to the poor soil structure in acidic soils, which affects crop root vigour. We found that bacterial diversity was significantly greater in soils of pH 6–8. Additionally, organic materials significantly elevated the diversity of bacteria in dryland soils and more significantly elevated fungal diversity in paddy soils, reducing the diversity of microorganisms in water-dry rotation soils and leading to the accumulation of dissolved organic carbon in water-dry rotation soils. Compared with unprocessed organic materials such as manure and straw, the application of composted organic materials in agricultural production can effectively increase soil carbon stocks and microbial richness.

In our analysis, organic material addition had a positive effect on soil organic carbon composition and microbial diversity. Although data selection was carefully limited to avoid misinterpretation of the results, there were still some limitations in this study. First, most current field studies only address the effects of organic materials on soil organic carbon composition or microbial diversity, and few cases are analysed in a single study. Although subgroup meta-analyses can be used to quantify factors such as climate and soil properties at different test sites, inconsistencies in the specific practices (e.g., application methods and organic material size) of different researchers may lead to differences in results. For instance, in agricultural practices, deep fertilization exhibits enhanced nutrient utilization compared to surface fertilization (Zhang et al., 2022a). The adoption of conventional tillage, as opposed to conventional tillage practices, can enhance the stability of soil aggregates, thereby facilitating carbon sequestration and promoting microbial diversity in the soil (Liu et al., 2023; Sae-Tun et al., 2022; Wang et al., 2017). In addition, existing studies usually only report data from a specific experimental phase rather than that from the continuous monitoring of soil active organic carbon and microbial diversity, which may bias our understanding of the relationship between organic

material on active organic carbon fractions and microbial diversity. Therefore, long-term continuous observations are necessary to understand the response of soil active organic carbon and microbial diversity to organic materials. Moreover, in the context of global climate change, the combined effect of climate change and organic matter addition on carbon sequestration and soil carbon use efficiency in agricultural soils and their coupling with microorganisms need to be further investigated.

## 5. Conclusions and future research prospects

Our study demonstrates that the enhancement of SOC (22.01%) is predominantly due to the increased POC fraction (42.35%). Additionally, DOC、MBC and EOOC exhibited respective increases of 20.72%, 26.93%, and 26.43%, following the incorporation of organic materials. This finding underscores the efficacy of organic amendments in boosting soil carbon sequestration. Furthermore, the model selection results revealed that organic material type as the most important factor affecting both soil active organic carbon and microbial diversity, with compost was the best material for enhancing soil carbon accumulation and microbial diversity. Structural equation revealed that there was a significant negative correlation between DOC and MBC, highlighting the intricate relationships within soil ecosystems under the influence of organic materials. To further elucidate the effects of organic materials on soil organic carbon and microbial diversity, we believe that the following aspects need to be further investigated:

(1) Although we quantified the positive effects of organic materials on the active organic carbon fraction and microbial diversity, current field studies are mostly focused on the individual effects of the soil organic carbon fraction or microbial diversity, and the coupled relationship between organic carbon fractions and microbial diversity is not clear.

(2) The addition of organic material enhances the soil C content. However, given the challenges posed by global climate change, it is imperative to investigate the combined impact of climatic factors and organic material addition on soil carbon sequestration and use efficiency in agricultural soils.

(3) Although the addition of organic materials has many benefits for soils, these materials can carry toxic and harmful substances. For example, compost and manure may contain heavy metals, antibiotics and excess salts that can accumulate in the soil. The continuing fermentation of straw after it is returned to soils may affect the growth of crop roots and increase pests and diseases, and excessive application of biochar may lead to soil pH changes or salinization, causing soil organisms to experience stress or die. Further research is required to develop effective measures for mitigating the adverse impacts of organic materials on soil in the future.

## CRediT authorship contribution statement

**Long Chen:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Wendong Qin:** Data curation. **Yifei Qiu:** Writing – review & editing, Data curation. **Mengmeng Zou:** Writing – review & editing. **Qiqi Yin:** Writing – review & editing. **Shenglu Zhou:** Writing – review & editing, Funding acquisition. **Qi Zhang:** Software, Data curation.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

Data will be made available on request.

## Acknowledgements

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2024.106128.

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